INSTRUCTION MANUAL

TDR100

Revision: 9/05

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TDR100

1. Introduction

This document presents operating instructions for the TDR100 and associated equipment and discusses time domain reflectometry (TDR) principles. Section 3 (Getting Started with TDR100 using PCTDR) describes a simple start-up configuration to quickly and easily display TDR probe waveforms using PCTDR.

The TDR100 can be controlled either by a computer using Windows software PCTDR or by using Instruction 119 with a CR10X or CR23X datalogger. PCTDR is used when display of waveform information is needed for setup and troubleshooting but does not support automated measurements at prescribed time intervals. The TDR100 and SDMX50 multiplexers can be configured for automatic control using the dataloggers.

A single TDR probe can be connected directly to the TDR100 or multiple probes connected via coaxial multiplexer units (SDMX50).

Warning

The TDR100 is sensitive to electrostatic discharge damage. Avoid touching the inner part of the panel BNC connector or the center rod of TDR probes connected to the TDR100.

1.1 TDR100 Packing List

The following are included with a TDR100.

1. PCTDR software and instruction manual on compact disk.
2. A 6 foot long, 9-conductor cable for connection between the serial port of a computer and the RS232 port of the TDR100.
3. Short 5-conductor cables for SDM connection between (a) datalogger and TDR100 and between (b) TDR100 and an SDMX50 coaxial multiplexer.

1.2 ENCTDR100 Packing List

The following are included with an ENCTDR100.

1. Enclosure Supply Kit; desiccant packs, humidity indicator, cable ties, putty and mounting hardware.
2. ENCTDR100 Enclosure Ground Wire Kit.
3. TDR100/SDMX50 Coaxial Interconnect Cable.
4. TDR100/SDMX50 and TDR100/Datalogger SDM 5-Conductor Cable.
5. Enclosure ENC 16/18 with two 1.7 inch diameter cable penetration ports.
6. Terminals for external deep cycle battery.

2. System Specifications

2.1 General

See the CR10X, CR23X, or CR1000 datalogger manuals for datalogger specifications.

2.2 Power Consumption

2.2.1 TDR100

- The current demand for the TDR100 during measurement is 270 milliamps.
- When the TDR100 is controlled by a datalogger, a 35 second timer puts the device in sleep mode requiring about 20 milliamps. After 35 seconds in sleep mode, a timer puts the TDR100 in standby mode requiring about 2 milliamps.
- When the TDR100 is controlled by PCTDR, a 60 second time-out puts the device in low power mode requiring about 60 milliamps.

2.2.2 SDMX50

- The quiescent current demand for the SDMX50 multiplexer is less than 1 milliamp.
- Current demand during switching is approximately 90 milliamps.
- All multiplexers of the same level switch simultaneously (see Figure 5-1). Switching takes less than 1 second.

2.3 TDR100 Performance Specifications

pulse generator output	250 mV into 50 ohms	
output impedance	50 ohms ± 1%	
time response of combined pulse generator and sampling circuit	≤ 300 picoseconds	
pulse generator aberrations	±5% within first 10 nanoseconds	
	±0.5% after 10 nanoseconds	
pulse length	14 microseconds	
timing resolution	12.2 picoseconds	
waveform sampling	20 to 2048 waveform values over chosen length	
	distance (V_p = 1)	time (1 way travel)
range	-2 to 2100 meters	0 to 7 microseconds
resolution	1.8 millimeter	6.1 picoseconds

waveform averaging	1 to 128
electrostatic discharge protection	internal clamping
power supply	unregulated 12 volt (9.6 V to 16 V), 300 milliamps maximum
temperature range	-40°C to 55°C
dimensions	210mm x 110mm x 55 mm
weight	700 g

2.4. Electromagnetic Compatibility

The TDR100 is Œ compliant with performance criteria available upon request. RF emissions are below EN55022 limit. The TDR100 meets EN61326 requirements for protection against electrostatic discharge and surge EXCEPT for electrostatic discharge on the center conductor of the panel BNC connector.

Warning

The TDR100 is sensitive to electrostatic discharge damage. Avoid touching the center conductor of the panel BNC connector or the center rod of TDR probes connected to the TDR100.

3. Getting Started with TDR100 using PCTDR

This section lists steps for a simple connection between a computer and the TDR100 to monitor a single TDR probe using PCTDR software. A single probe is connected directly to the TDR100, and no multiplexers are used. TDR100 operation with SDMX50 multiplexers is described in Section 5.7.

1. Install PCTDR

The following instructions assume that drive D: is a CD-ROM drive. If the drive letter is different, substitute the appropriate drive letter.

- Put the installation disk in the CD-ROM drive. The intall appllication should come up automatically. If the install does not start, use Start | Run of the Windows system and type D:/Disk1/Setup.exe or use the Browse button to access the CD-ROM drive and select the setup executable file in the Disk1 folder

- The PCTDR Installation Utility is activated. Follow the prompts to complete the installation.

2. Use the supplied 9 conductor cable to connect a computer to the RS232 connector on the TDR100

The RS232 connector on the TDR100 is used for communication between a serial communication port of a computer and the TDR100. A 9-conductor cable is supplied with the TDR100. Serial communication port

1 is the default setting and can be changed in PCTDR menu Settings/Communications. The baud rate is factory set to 57600.

3. **Connect 12 volt power to TDR100**

   12 volt power to the TDR100 is connected using terminals +12V and GROUND on the panel 5-terminal connector. An external power supply or the 12V terminals of a datalogger can be used for power. The C1, C2 and C3 terminals are for SDM (synchronous device for measurement communication protocol) communications. The C1, C2 and C3 terminals are not used for single probe monitoring with a computer using PCTDR.

4. **Connect a TDR probe to the BNC connector of the TDR100**

5. **Start PCTDR by selecting PCTDR under Programs of the Windows Start Menu or double-clicking the PCTDR icon.**

6. **View a waveform using Get Waveform**

   In the Waveform section of PCTDR, set *Start* to 0 or 1 m and *Length* to the apparent length (see note below) of the attached probe cable plus 5 meters. Press *Get Waveform*.

3.1 Discussion of Distances and Propagation Velocity (V_p) when using TDR100

A TDR system is typically comprised of components with different signal propagation properties. The V_p for a particular component depends on transmission line characteristics such as the dielectric constant of inter-conductor insulating material. Setting V_p = 1.0 and using apparent distances simplifies system setup. The displayed position of a waveform is apparent distance. The value chosen for V_p does not affect water content or electrical conductivity measurement. The selected V_p value does affect waveform display.

The relationship between real and apparent distance is given as

apparent distance = (actual distance) x (selected V_p/actual V_p).

For example, if the actual length of a cable having a V_p of 0.78 is 5 meters and the selected V_p is 1.0, the apparent distance to the end of the cable is 5 x (1.0/0.78) = 6.41 meters. Typical cable V_p's range from 0.67 to 0.9. Campbell Scientific TDR probes use RG-58 with a Vp of 0.67 and RG-8 with a Vp of 0.78.

An example is presented in Figure 3-1. Displayed is the waveform for a CS610 in water. The actual cable length is about 5 m. The apparent cable length is about 6 m.

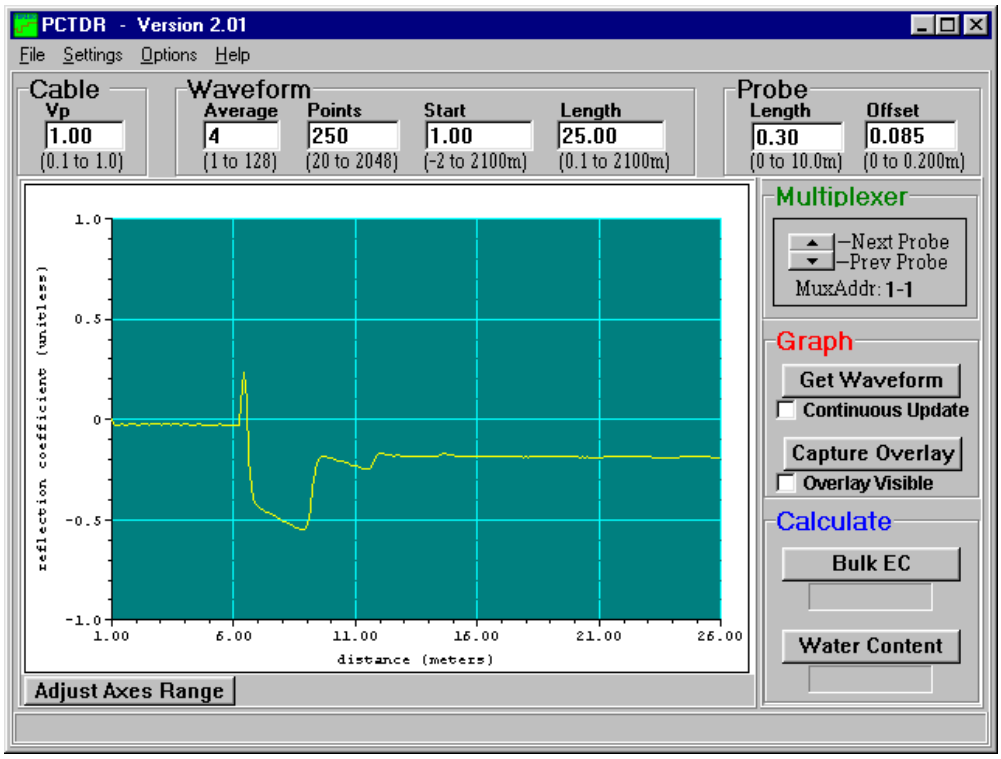


FIGURE 3-1. Waveform of a CS610 in water.

Changing the W*aveform Start* value to 5.7 m and the W*aveform Length* to 5 m gives the waveform displayed in Figure 3-2.

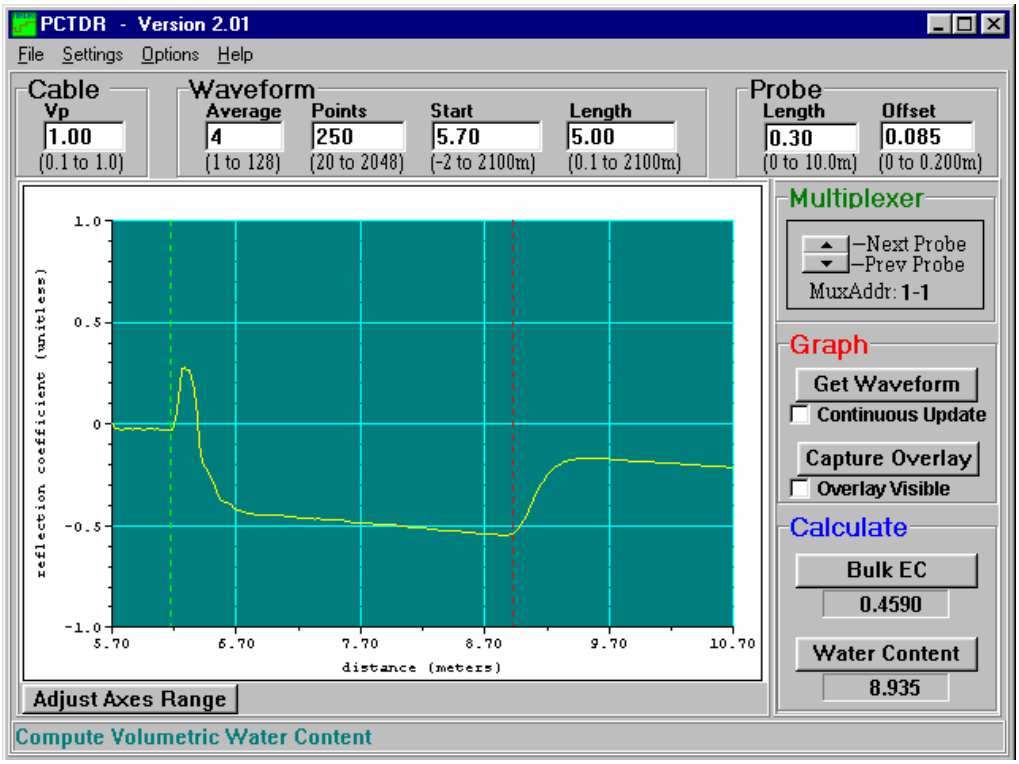


FIGURE 3-2. Waveform of CS610 in water after changing Start and Length parameters to display relevant portion of reflected signal.

3.2 PCTDR Help

Information on PCTDR is available from the HELP menu or by pressing F1. Using F1 gives specific help associated with the position of the cursor or active screen. See Section 4.2 for PCTDR HELP details.

4. PCTDR Software

A display for viewing waveforms is generally needed only for system setup and troubleshooting, and the TDR100 does not have a built-in display. Windows software PCTDR is used with a personal computer to configure the TDR100 and multiplexers and display waveforms.

NOTE Conflicts between commands simultaneously issued by a datalogger and PCTDR will cause error messages in PCTDR . To prevent these errors, halt the datalogger program while controlling the TDR100 with PCTDR. Halting the program can be accomplished by setting the datalogger table execution interval to zero.

Note for use of PCTDR when TDR100 is connected to CR23X or CR1000 datalogger

When the TDR100 is connected to a CR23X or CR1000 datalogger using control ports 1-3 for SDM control and SDMX50 multiplexers are also connected, an instruction must be used in the datalogger program to properly configure the control ports. If this is not done, PCTDR will not control the multiplexers. This is required because the CR23X and CR1000 control ports present a low impedance to the SDM lines and this will load the signal issued by TDR100 when PCTDR is used to control multiplexers.

At the end of the CR23X datalogger program containing TDR100 instruction (P119), use an instruction (P20) to configure control ports 1, 2 and 3 as input.

Set Port(s) (P20)
1:9999 C8..C5 = nc/nc/nc/nc
2:9888 C4..C1 = nc/input/input/input

At the end of the CR1000 datalogger program containing TDR100 instruction (TDR100), use an instruction (PortsConfig) to configure control ports 1, 2 and 3 as input.

PortsConfig (&B00000111,&B00000000)

4.1 General

PCTDR requires a connection from a COM port of the computer to the RS232 port of the TDR100. Choice of COM port and baud rate is made in PCTDR menu *Settings/Communications*. The baud rate is set during TDR100 production to 57600.

4.2 PCTDR Help

There are several ways to access PCTDR's help system:

- The help file's Table of Contents can be opened by choosing Help | Contents from the PCTDR menu.
- The help file's Index can be opened by choosing Help | Index from the PCTDR menu.
- At any time you can press F1 for help that is relevant to cursor position.
- If the help file is opened, pressing the Contents button on the help system's toolbar will open the Table of Contents.
- If the help file is opened, choosing the Index button from the help system's toolbar will bring up the Index. Keywords can be typed in to search for a topic. An in-depth search can be performed by pressing the Find button and typing in a word.

If a highlighted link takes you to another topic, you can return to the original topic by selecting the Back button from the help system's toolbar.

4.3 Menu Selections

4.3.1 File Menu

Save Configuration/Load Configuration - save and reload configuration of user-selectable parameters. Saves configuration as .wfd file.

Save ASCII Waveform - save displayed waveform as .dat file.

Save Mux Setup/Load Mux Setup - save and reload multiplexer setup. Saves as .mux file.

Print Graph - send displayed graph to default printer

Exit - quit PCTDR

4.3.2 Settings Menu

Communication - select communication serial port and baud rate

Waveform Selection - select reflection waveform or reflection waveform plus first derivative

Multiplexer - configure multiplexer switching

Calibration Function - select calibration functions for volumetric water content and bulk electrical conductivity

Units - select meters or feet

4.3.3 Options Menu

Terminal Emulator - line command mode of PCTDR

Advanced - link for downloading TDR100 operating system

4.4 PCTDR Parameter Selection Boxes

4.4.1 Cable

The cable propagation velocity, Vp, depends on the dielectric constant of the insulating material between the coaxial cable center conductor and outer shield. The value entered in this parameter selection box is the ratio of the actual propagation velocity for a selected medium to the propagation velocity in a vacuum (3×10^8 m sec^{-1}). Specific V_p values for each coaxial cable are available from manufacturer data books. It is only necessary to know the V_p value if the TDR100 is used as a cable tester for finding cable lengths or faults.

See Section 3.1 for a discussion of propagation velocity.

Calculation of water content or electrical conductivity is independent of the chosen value for V_p because V_p cancels in the calculation. However the V_p value does affect waveform display.

For water content measurements, it is recommended that propagation velocity, Vp, be set at 1.0.

4.4.2 Waveform

Average - sets the number of measurements averaged at a given distance from the TDR100. A value of 4 is recommended. Higher values can be used when noise is present. Averaging is useful when noise from power sources or when noise of random nature is superimposed on the reflection waveform. Averaging is accomplished by collecting *n* values at a given distance before collecting values at the next distance increment where *n* is the value entered in *Average*.

Points - the number of points in the displayed or collected waveform (using *File/Save ASCII Waveform*). For water content measurements, a value of 251 is recommended and will provide 250 waveform increments. A higher value can provide better resolution when collecting waveforms.

Start - the apparent distance from the TDR100 to where the displayed waveform will begin (using *File/Save ASCII Waveform*). For water content measurements this value should be the apparent distance from the TDR100 to the beginning of the probe minus approximately 0.5 meter. Figure 3-2 is an example of the display when the correct start is chosen.

NOTE The apparent distance is the (actual distance) x (selected Vp/actual Vp). For example, if the actual length of a cable having a Vp of 0.78 is 5 meters and the selected Vp is 1.0, the apparent distance to the end of the cable is 5 x (1.0/0.78) = 6.41 meters.

Length - Beginning at distance *Start*, the length of the display window and apparent length depicted by the number of data *Points* selected. For water content measurements with the CS605 or CS610 TDR probes (30 cm rods) a length of 4 meters is recommended. See Table 1.

4.4.2.1 A Discussion of Start and Length Parameters

Only the waveform reflection near the probe is used for water content determination. The reflections for most of the cable between the TDR100 and the TDR probe are not used for TDR100 measurements. The apparent probe length algorithm begins analysis of the probe waveform at the distance set by *Waveform Start*. The *Waveform Start* value must include a short section of cable near the probe head to establish reference values. Subtracting 0.5 m from the PCTDR x-axis value for the actual probe beginning is recommended. The actual beginning of the probe displayed in Figure 4-1 is approximately 6.2 m. A Waveform Start value of 5.7 m will provide the complete data needed by the algorithm to determine apparent probe length.

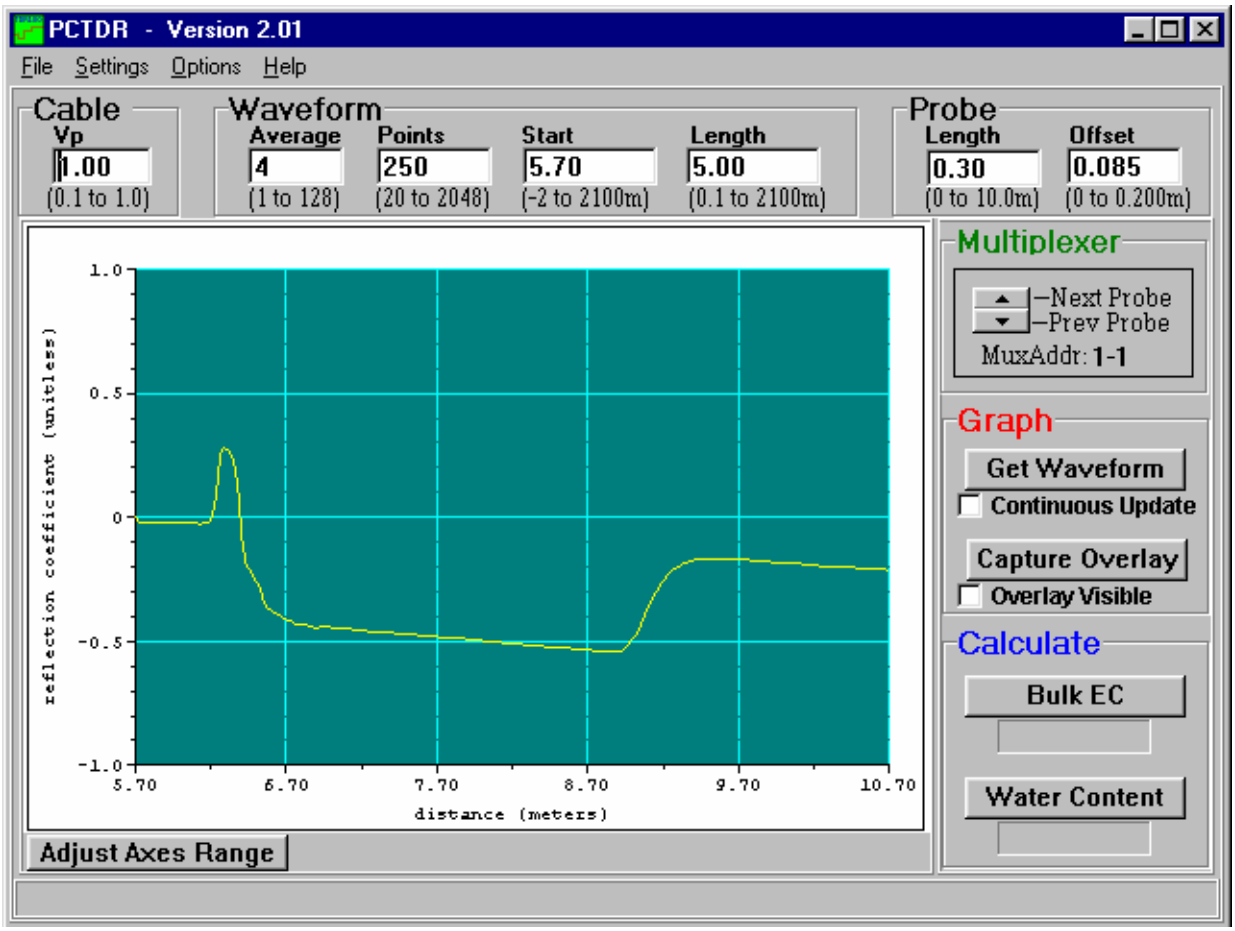


FIGURE 4-1. PCTDR waveform for CS610 in water.

The algorithm will use the length of the waveform set by the *Waveform Length*. After finding the probe beginning, the algorithm searches over the remaining waveform for the end of the probe. The length must be large enough to display a short distance past the end of the probe under the wettest expected conditions.

TABLE 4-1. Recommended Waveform Length values for range of TDR probe rod lengths assuming soil porosity of 0.60.

Probe rod length (m)	Recommended Waveform Length value (m)
0.10 to 0.20	3
0.21 to 0.30	4
0.31 to 0.40	5
0.41 to 0.6	6
0.61 to 0.75	7
0.76 to 1.00	9

Use the recommended values listed in Table 1 or use the following equation to estimate the required window length, L_w.

$$L_w = \frac{L \cdot \left(\theta_{v-\max} + 0.176\right)}{0.114} + 2$$

with L the actual probe rod length, and, $\theta_{v\text{-}max}$ the maximum expected volumetric water content. Two m is added for the .5 m before the probe and some distance after the probe end. For example, using a CS610 with 0.3 m probe rod length in a soil with a porosity of 0.6 gives an estimated apparent probe length of 4.04 m. Setting the Waveform Length to 4 m is recommended.

5. System Components: Datalogger Control

5.1 General

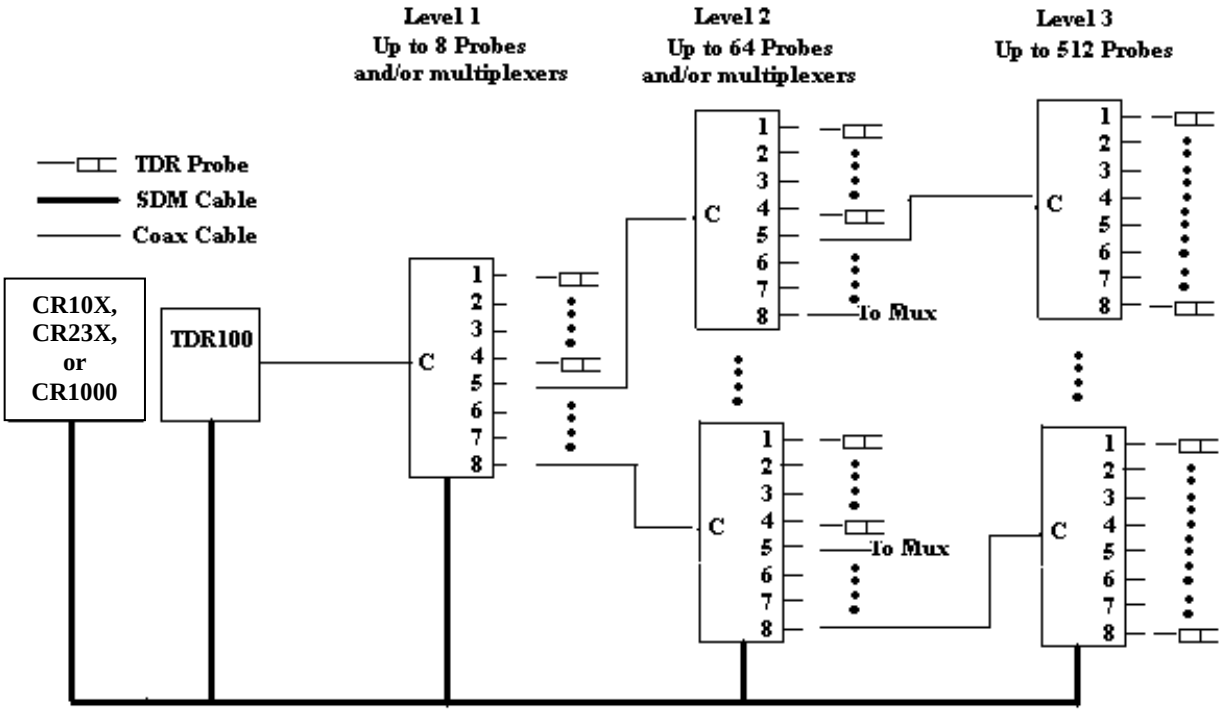


FIGURE 5-1. TDR System Components

5.2 Datalogger

Campbell Scientific CR10X and CR23X dataloggers use Instruction 119 and various other instructions to control the TDR100 measurement sequence and store the resulting data. PC208W (version 3.1 or higher) or LoggerNet are used to link the datalogger to a computer for data and program transfer.

Campbell Scientific CR1000 dataloggers use Instruction "TDR100" to control the TDR100 measurement sequence and store the resulting data. PC400 or

LoggerNet (version 3.0 or higher) are used to create and send the CRBasic Program to the CR1000 datalogger.

5.3 TDR100

The TDR100 contains the pulse generator for the signal applied to a TDR probe. The TDR100 also digitizes the reflection and applies numerical algorithms for measuring volumetric water content or electrical conductivity. The TDR100 communicates with the datalogger using SDM protocol or with a computer using PCTDR and serial communications.

5.4 Power Supply

The system operates on 12 V power. A user supplied deep cycle 12 V lead acid battery is commonly used in remote installations. Two terminal strip adapters for the battery posts are provided with the ENCTDR100 (see Figure 5-2). These terminal strips will mount to wing nut battery posts found on most deep cycle lead acid batteries. Installations with AC power available should use it to continuously charge the system battery. Remote installation without AC power should keep the battery charged with an SP10R or SP20R solar panel. See the applications note at ftp://ftp.campbellsci.com/pub/outgoing/apnotes/pow-sup.pdf for discussion of power supplies.

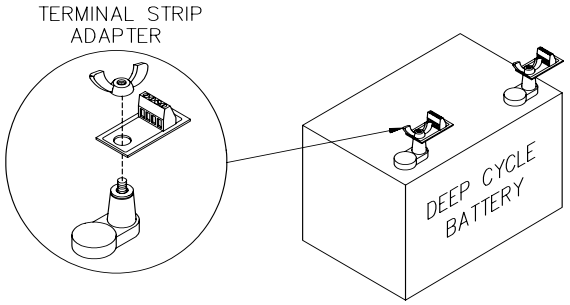


FIGURE 5-2. Terminal Strip Adapters for Connections to Battery

Campbell Scientific recommends using datalogger switched 12 volts to power the TDR100. This will provide power savings and will automatically reset the TDR100 and provide automatic recovery from system malfunctions. This practice can reduce loss of measurement data when a problem exists. Typically the switched 12 volts is turned on at the beginning of the datalogger program table that contains the TDR measurement instructions, and it is turned off at the end of the table. CR10X and CR23X datalogger Instruction 86 can be used to set a control port for the switched 12 volt power. PC208W or LoggerNet HELP provide guidance for controlling switched 12 volts with both the CR10X and CR23X. See datalogger programming example 1 in program example section of this manual. CRBasic Instruction “SW12” can be used to switch 12 volt power on the CR1000 datalogger. See programming example 6 in the program example section of this manual.

5.4.1 Grounding

The TDR system should be installed with a single ground point. A good earth ground should be established close to the datalogger/TDR100.

A copper clad grounding rod comes with the model CM6 or CM10 tripod. The UTGND kit provides hardware needed for grounding rod use.

The dataloggers, TDR100 and SDMX50SP multiplexer have grounding lugs. These lugs should be tied together with short pieces of grounding wire no smaller than 12 AWG. The ENCTDR100 has a grounding lug in the lower left corner of the enclosure. A piece of 10 AWG is provided for connection to the components in the enclosure. A short run of heavy gage (10 AWG or heavier) wire should be connected from the enclosure lug to earth ground.

The ground lug on peripheral SDMX50 multiplexer enclosures should only be used if the multiplexer is close enough to conveniently use the same ground point as the datalogger.

5.5 SDM Communication

5.5.1 SDM Addressing for TDR100 System

SDM (Synchronous Device for Measurement) communication protocol is used with the TDR100, SDMX50 and Campbell Scientific dataloggers to control measurements and transfer data. Datalogger control ports 1, 2 and 3 are dedicated to SDM functions DATA, CLOCK and ENABLE, respectively. The use of synchronous communications requires adherence to an addressing scheme for all communicating devices.

SDM cables have 5 conductors. The red and black wires are typically used for 12 volt and ground. The remaining 3 wires connect the control lines. One is used to connect control port 1 of the datalogger to C1 of each of the other components of the system, e.g. TDR100 and SDMX50 multiplexer. Similarly for C2 and C3. If PCTDR is being used to control multiplexers, the control lines connect C1, C2 and C3 of TDR100 and multiplexer(s).

The SDM address of the TDR100 is set using the thumbwheel switch on the TDR100 front panel. The address selected on the TDR100 must match the SDM Address used in the CR10X/CR23X/CR1000 datalogger program.

Addressing for the SDMX50 is selected with hardware jumpers. Changing the SDMX50 jumpers requires removing the multiplexer front cover. See Figure 5-4 and Table 5-1.

There are a maximum of three hierarchical multiplexer levels (see Figure 5-1). The level 1 multiplexer has an address value equal to the TDR100 address plus 1. Level 2 multiplexers have an address value equal to the TDR100 address plus 2 and the level 3 multiplexers have an address value equal to the TDR100 address plus 3. See Table 5-1 for SDM address nomenclature.

It is recommended to use a TDR100 address of 0, level 1 SDMX50 address of 01, level 2 SDMX50 address of 02, and level 3 SDMX50 address of 03.

TABLE 5-1. SDM Addressing

Base 10 Number	Instruction 119 Address (Base4)	TDR100 Thumbwheel Switch	Level 1 SDMX50 Mux (TDR100+1) MSD LSD	Level 2 SDMX50 Muxs (TDR100+2) MSD LSD	Level 3 SDMX50 Muxs (TDR100+3) MSD LSD
0	00	0	0 1	0 2	0 3
1	01	1	0 2	0 3	1 0
2	02	2	0 3	1 0	1 1
3	03	3	1 0	1 1	1 2
4	10	4	1 1	1 2	1 3
5	11	5	1 2	1 3	2 0
6	12	6	1 3	2 0	2 1
7	13	7	2 0	2 1	2 2
8	20	8	2 1	2 2	2 3
9	21	9	2 2	2 3	3 0
10	22	A	2 3	3 0	3 1
11	23	B	3 0	3 1	3 2
12	30	C	3 1	3 2	3 3
13	31	D	3 2	3 3	*not available*
14	32	E	3 3	*not available*	*not available*
15	33	F	*not available*	*not available*	*not available*

5.5.2 SDM Cable and Cable Length Considerations

5-conductor cable with shield and drain is used for interconnection of SDM devices. The 5 conductors are used for 12 volt power, ground and the 3 SDM lines. A cable assembly (pn13776) is provided with the TDR100 and the ENCTDR100. This assembly is for SDM connection between the TDR100 and a datalogger and between the TDR100 and a SDMX50 multiplexer. Additional cable for SDM connection to other TDR system components is available from Campbell Scientific as part SDMCBL-L with -L the cable length in feet. The maximum recommended total length of all SDM cables should not exceed 500 feet. Lengths greater than 500 feet can give unreliable communication between SDM devices.

SDM communications use datalogger control ports 1, 2 and 3. No other devices should be connected to these control ports.

The insulation for the individual wires of the SDM cable affects the frequency response and reliability. PVC insulation has more attenuation than polypropylene or polyurethane and should not be used for SDM communication except when total SDM cable length is less than 250 feet.

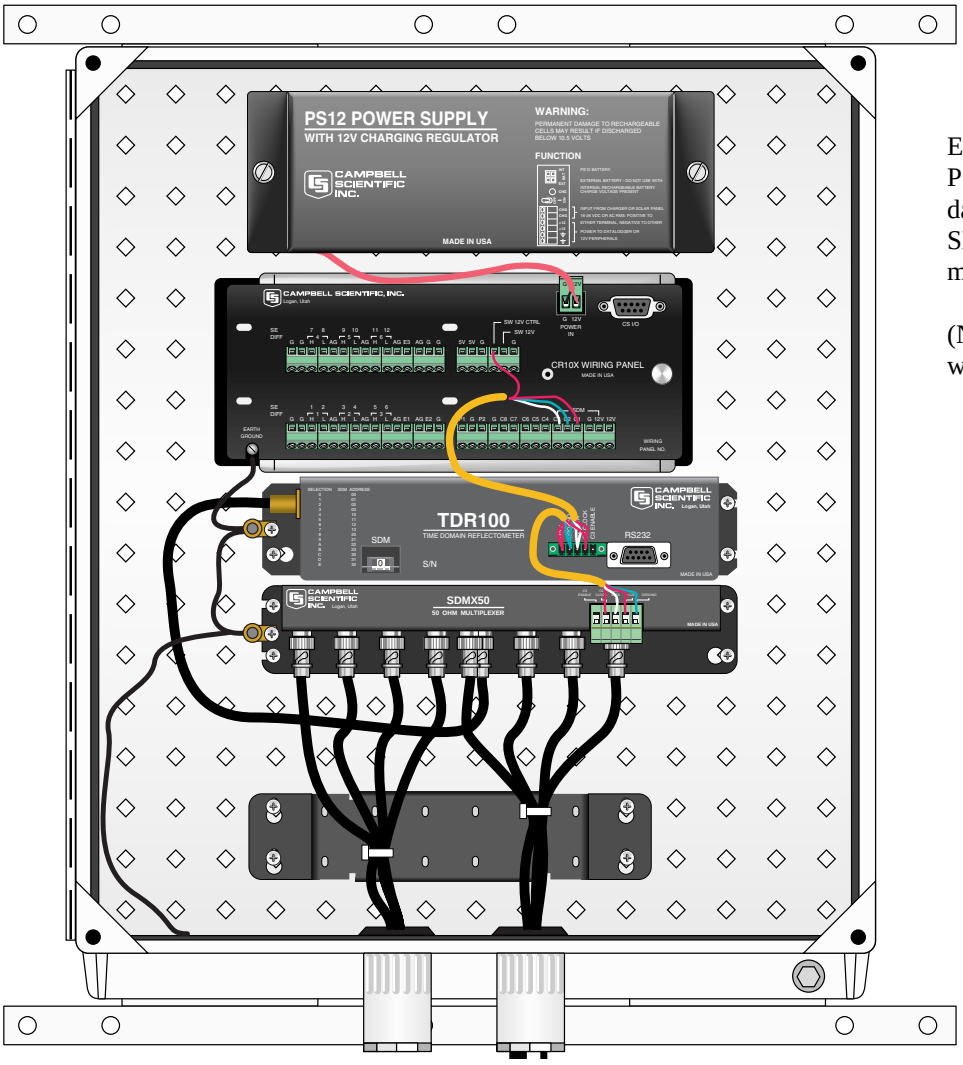
5.6 ENCTDR100

Many TDR system applications require installation of equipment at field sites. The ENCTDR100 is a weather-proof enclosure with a mounting plate for a CR10X, CR23X, or CR1000 datalogger, power supply, TDR100, SDMX50SP, cable strain relief bracket and associated cabling. The ENCTDR100 can be mounted on a CM6 or CM10 tripod for free-standing installation.

5.6.1 Mounting Equipment in ENCTDR100

The ENCTDR100 is a 16” x 18” weathertight enclosure that is modified for use with a Campbell Scientific TDR system. The ENCTDR100 comes with the following parts:

1. Enclosure Supply Kit; desiccant packs, humidity indicator, cable ties, putty and mounting hardware.
2. ENCTDR100 Enclosure Ground Wire Kit.
3. TDR100/SDMX50 Coaxial Interconnect Cable.
4. TDR100/SDMX50 and TDR100/Datalogger SDM 5-Conductor Cable.
5. Enclosure ENC 16/18 with two 1.7 inch diameter cable penetration ports.
6. Terminals for external deep cycle battery.



ENCTDR100 shown with PS12 power supply, CR10X datalogger, TDR100, and SDMX50SP coaxial multiplexer.

(Not intended to be used as wiring guide.)

5.7 SDMX50

The SDMX50 is a 50 ohm, eight-to-one, coaxial multiplexer. The same multiplexer circuit is packaged as the SDMX50, the SDMX50LP or the SDMX50SP. The SDMX50 is designed to minimize signal attenuation and all channels have equal transmission line lengths. Spark gaps provide protection

from voltage surge damage. Figure 5-3 describes typical signal attenuation from the common to one output channel for frequency range important for TDR measurements.

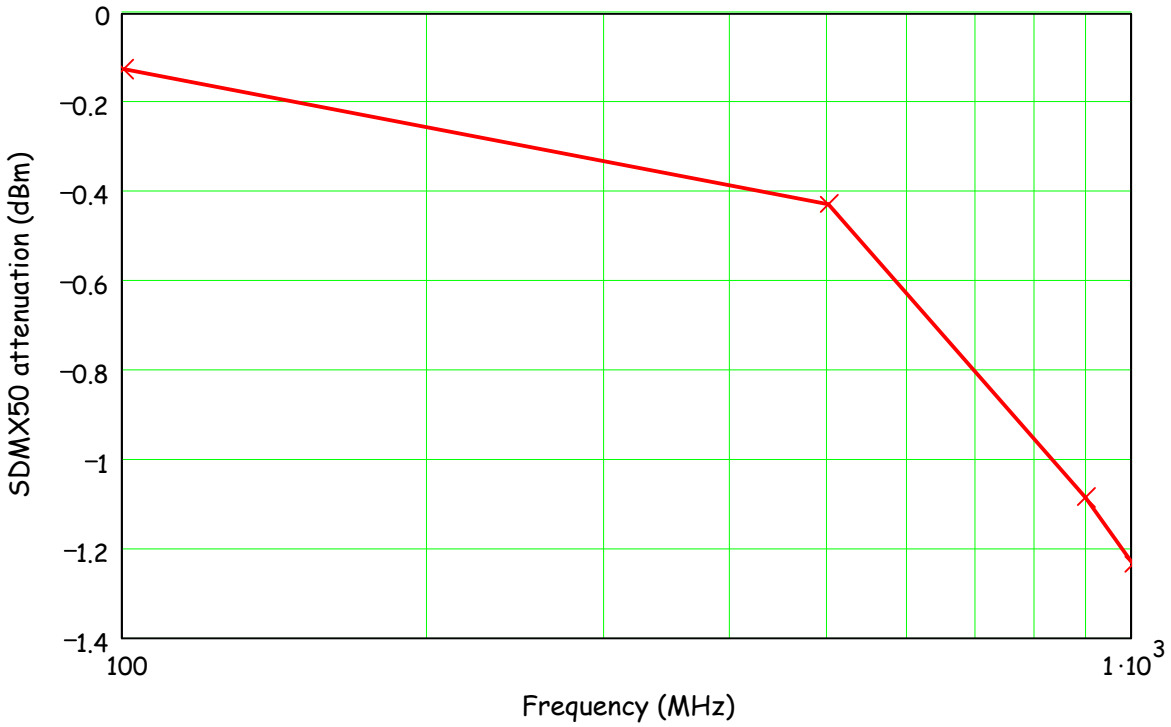


FIGURE 5-3. SDMX50 signal attenuation.

Each of the eight ports can be connected to a probe or another multiplexer (see Figure 5-1).

The multiplexers use synchronous communications and require address coordination with the datalogger. See Section 5.5 for a discussion of SDM communications and addressing. Figure 5-4 shows the location of jumpers used for SDMX50 addressing.

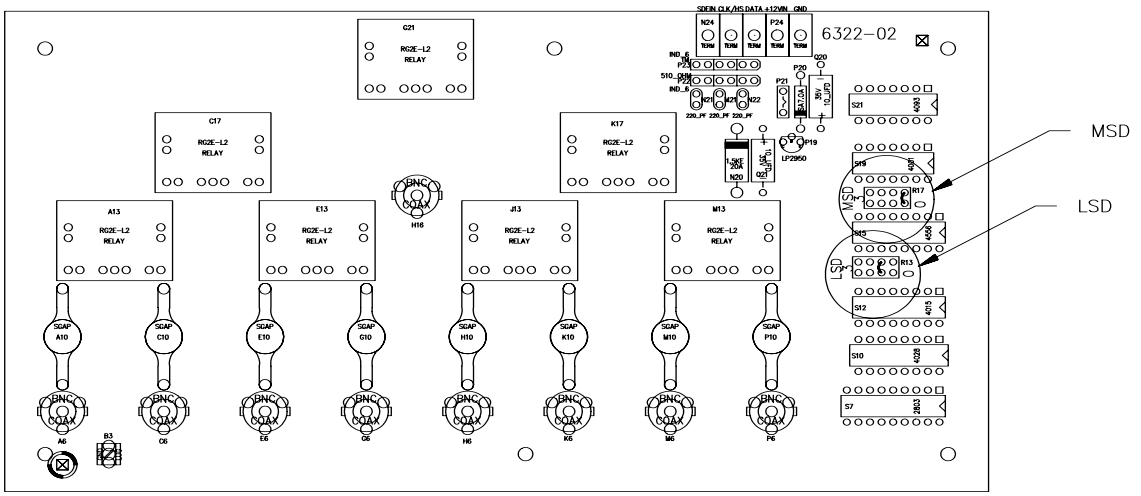


FIGURE 5-4. Location of Address Jumpers on SDMX50

5.8 Soil Probes

The TDR probes are the sensors of the TDR measurement system and are inserted into the medium to be measured. The probes are a wave guide extension on the end of coaxial cable. Reflections of the applied signal along the waveguide will occur where there are impedance changes. The impedance value is related to the geometrical configuration of the probe (size and spacing of rods) and also is inversely related to the dielectric constant of the surrounding material. A change in volumetric water content of the medium surrounding the probe causes a change in the dielectric constant. This is seen as a change in probe impedance which affects the shape of the reflection. The shape of the reflection contains information used to determine water content. Both volumetric water content and electrical conductivity can be measured using fixed spacing 2-rod designs and 3-rod designs (CS605 and CS610).

Campbell Scientific TDR Probes

	CS605	**CS610**
General Description	3-rod probe no balun required stainless steel rods	3-rod probe no balun required stainless steel rods
Dimensions	Rods: 30 cm length 0.476 cm diameter Probe head: cable-to-rod 10.8 cm width 7.0 cm thickness 1.9 cm	Rods: 30 cm length 0.476 cm diameter Probe head: cable-to-rod 10.8 cm width 7.0 cm thickness 1.9 cm
Cable type	RG58	RG8 low loss
Cable length	user-specified length	user-specified length
Probe offset factor	0.085 m	0.085 m
Probe constant for electrical conductivity (Kp) *see Section 5.8.1	1.74	1.74

5.8.1 Determining Probe Constant, K_p, using PCTDR

Section 6.2.6 presents the principles for TDR measurements of soil electrical conductivity. The result of the measurement must be multiplied by the probe constant (K_p) to give bulk electrical conductivity in S/m (Siemens/meter). The K_p value can be measured using PCTDR. The method requires submersion of the TDR probe rods in de-ionized water of known temperature. See PCTDR HELP for simple instructions.

6. Datalogger Instructions for TDR Measurements

6.1 CR10X and CR23X Datalogger Instruction 119

parameter		data type	value	description
SDM address	1:	2	$(00)_4$ to $(33)_4$	Address of TDR100 see Table 5-1
Output option	2:	4	0	Returns L_a/L
			1	Returns vector of n + 9 values from TDR100 with n the number of waveform data points selected. Elements 1-9 contain key Instruction 119 parameter values. Then next n elements are reflection waveform values.
			2	Returns the waveform plus the first derivative of the waveform
			3	Electrical conductivity option. See section on probe constants for electrical conductivity measurements.
Multiplexer and probe selection	3:	4		See Section 5.1.1 for address protocol
Waveform Averaging	4:	FP	1 - 128	Number of reflections averaged by the TDR100.
V_p	5:	FP	.1 - 1	relative propagation velocity
Points	6:	FP	20-2048	number of points in waveform
Cable length (meters)	7:	FP	0 - 2100	distance for TDR100 corresponding with beginning of waveform
Window Length (meters)	8:	FP	.1 - 700	length of reflection waveform
Probe length	9:	4		Physical length of the exposed portion of the metal rods
Probe offset	10:	FP	0 - 1.0	Accounts for portion of rods not exposed to soil. See Section 6.2.10.
Input location	11:	4		Input storage location for measurement result. If waveforms are chosen for output, this location is occupied by the first data point.
Multiplier	12:	FP		Multiplication factor applied to La/L and stored in input location specified in parameter 11. Set to 1 when parameter 2 is 1 or 2. For electrical conductivity, can be used for probe constant value.
Offset	13:	FP		Offset value added to La/L and stored in input location specified in parameter 11. Set to 0 when parameter 2 is 1 or 2.

6.2 Discussion of TDR Instruction Parameters (Instruction 119)

6.2.1 Parameter 1: SDM Address

The SDM address of the TDR100 is set by selecting hexadecimal values with the thumbwheel switch on the TDR100 front panel. Instruction 119 requires a 2 digit integer that is the base 4 value of the TDR100 address. See Table 5-1

6.2.2 Parameter 2: Output Option

6.2.2.1 Enter 0: Measure La/L

In the section on TDR Principles, the equation

$$\sqrt{K_a} = \frac{L_a}{L}$$

is presented. The terms of this equality can be related to volumetric water content using empirical relationships such as equations [3] and [4] shown in Section 7. The apparent length of the probe rods, L_a, changes with water content. Dividing L_a by the real rod length, L, gives the square root of dielectric constant. The L_a/L value is empirically related to volumetric water content using calibration functions of the form $\theta_v = f(L_a/L)$. See Section 7 for commonly used calibration functions.

6.2.2.2 Enter 1: Collect Waveform

The digitized reflection waveform can be collected from the TDR100 by the datalogger in ASCII format. Datalogger input storage must be manually allocated for the waveform data points using "block allocation" in Edlog datalogger software. The waveform is collected as an array. The first 9 cells of the array is a header and contain values entered in Instruction 119. Waveform values fill the rest of the array. Always allocate 9 more cells in datalogger input storage than the number of datapoints chosen in parameter 6. See Section 6.2.11.1 for header information.

6.2.2.3 Enter 2: Collect Waveform and First Derivative

The reflection waveform and the first derivative are written to datalogger input storage. Input storage must be manually allocated. See Section 6.2.6. The required number of input locations is twice the number of points (instruction Instruction 119, parameter 6) plus 9 for the header information.

6.2.2.4 Enter 3: Measure Bulk Electrical Conductivity

The electrical conductivity routine in the datalogger returns the value

$$\frac{1}{Z_c}\frac{1-\rho}{1+\rho}$$

which must be multiplied by the probe constant, K_p, to get an electrical conductivity value. Kp is entered in Instruction 119 parameter 12. See

Section 7 for discussion of the electrical conductivity measurement method and Section 6.2.13.1 for discussion of Kp..

6.2.3 Parameter 3: Multiplexer and Probe Selection

Addressing scheme: ABCn

Where:

A -- Level 1 multiplexer channel
B -- Level 2 multiplexer channel
C -- Level 3 multiplexer channel
n -- the number of consecutive probes; addressing starts with the channel specified for the highest level multiplexer.

Note: enter a 0 when a level is not used.

Example 1

An entry of ***1008***:

Entry	**Description**
1	channel 1 is specified for the level 1 multiplexer.
0	the level 2 multiplexer is not used.
0	the level 3 multiplexer is not used.
8	8 consecutive probes are read; the probes are connected to channels 1, 2, 3, 4, 5, 6, 7, and 8 of the level 1 multiplexer.

Example 2

An entry of ***3624***:

Entry	**Description**
3	channel 3 is specified for the level 1 multiplexer.
6	channel 6 is specified for the level 2 multiplexer.
2	channel 2 is specified for the level 3 multiplexer.
4	4 consecutive probes are read; the probes are connected to channels 2, 3, 4, and 5 of the level 3 multiplexer.

6.2.4 Parameter 4: Waveform Averaging

Sets the number of measurements averaged at a given distance from the TDR100. A value of 4 is recommended. Higher values can be used when noise is present. Averaging is useful when noise from power sources or when noise of random nature is superimposed on the reflection waveform. Averaging is accomplished by collecting *n* values at a given distance before collecting values at the next distance increment where *n* is the value entered in *Average*.

6.2.5 Parameter 5: Relative Propagation Velocity

Relative propagation velocity is the ratio of actual propagation velocity for a transmission line to the propagation velocity in air. A TDR system is typically comprised of components with different signal propagation properties. The V_p for a particular component depends on transmission line characteristics such as the dielectric constant of inter-conductor insulating material. Setting $V_p = 1.0$ and using apparent distances simplifies system setup. The displayed position of a waveform is apparent distance. The value chosen for V_p does not affect water content or electrical conductivity measurement. The selected V_p value does affect waveform display.

6.2.6 Parameter 6: Points

The number of waveform values used to calculate apparent lengths or collected as a waveform file. A value of 251 is recommended. A higher value can provide higher resolution but can also be problematic in noisey environments. The first data point is a relative zero and corresponds with the value of Cable Length. If 250 spatial increments are desired to span the desired Window Length, a value of 251 should be chosen.

6.2.7 Parameter 7: Cable Length (meters)

Cable length is used by the waveform analysis algorithm as the start position to search for the probe beginning and end. It is an apparent length.

The value for cable length is easily found using PCTDR. Select the probe using the *Multiplexer* feature in the *Settings* menu. Then adjust the cable length and window length to position the waveform so the distance to the beginning of the probe can be read from the x-axis. Subtract 0.5 meters from the beginning distance and use that value in parameter 7 of datalogger instruction 119.

It is important that the V_p used during determination of value for cable length be the same V_p used during subsequent measurements with PCTDR and datalogger instruction 119. A Vp value of 1.0 is recommended for soil water measurements.

6.2.8 Parameter 8: Window Length (meters)

Window length specifies the length of waveform used in water content determination and the distance for a saved waveform. The waveform analysis algorithm begins at the distance specified by cable length and uses data contained for the value specified by Window Length. It is important that Window Length be large enough to contain the entire probe waveform at the highest expected water contents. See Table 4-1.

6.2.9 Parameter 9: Probe Length (meters)

Physical length of the exposed portion of the TDR probe rods.

6.2.10 Parameter 10: Probe Offset (meters)

Most TDR probes have a block of epoxy or other material which holds the rods rigidly spaced and houses an impedance matching transformer (balun) if used. The algorithm in the TDR100 uses changes in the reflection coefficient to identify end points of the probe. The transition from the coaxial cable to the TDR probe occurs inside the probe block and causes an increase in the reflection coefficient if the probe impedance is greater than the cable impedance. However, this is not the same physical position as the beginning of the probe's exposure to the soil being measured. Therefore, a correction must be made for the distance which the signal travels inside the probe block. This offset is determined empirically. For the CS600 probe, the value is 69 mm (enter 0.069 in parameter 10), and for the CS605 and the CS610, the value is 85 mm (enter 0.085 in parameter 10). The offset for probes not obtained from Campbell Scientific must determined by the user. Contact Campbell Scientific for guidance.

6.2.11 Parameter 11: Input Location

Input storage location for measurement result. If waveforms are chosen for output, this location is occupied by the first data point.

6.2.11.1 Reflection Waveform Values to Input Storage

Saving reflection waveforms or reflection waveform plus first derivative using Instruction 119 requires manual allocation of datalogger input storage. The Insert Block function of the Edlog input location editor is used to allocate input locations for the waveform array header elements (see Table 6-1) and waveform values. The array header contains nine elements. The minimum number of locations that must be allocated is the *Points* value defined in Instruction 119 parameter 6 plus 9. An array size allocation of 9 more than the number of waveform points the minimum.

TABLE 6-1. Reflection waveform array header elements.

Description of Array Header Elements	
1	averaging
2	propagation velocity
3	number of data points
4	cable length
5	window length
6	probe rod length
7	probe offset
8	multiplier
9	offset

6.2.12 Parameter 12: Multiplier

Multiplication factor applied to the value stored in the input location specified in parameter 11. Set to 1 when parameter 2 is 1 or 2. The multiplier can be used for the probe constant value when measuring electrical conductivity.

6.2.13 Parameter 13: Offset

Offset value added to the value stored in input location specified in parameter 11. Set to 0 when parameter 2 is 1 or 2.

6.2.13.1 Probe Constant for Electrical Conductivity Measurement

The section, TDR Principles, presents the equation used for soil bulk electrical conductivity. For convenience, it is repeated here.

$$\sigma = \frac{K_p}{Z_c}\frac{1-\rho}{1+\rho}$$

A portion of the datalogger algorithm evaluates the reflected waveform to determine the applied and reflected voltages. From this, the reflection coefficient, ρ, can be calculated. The term, Z_c, is the reflectometer impedance and is a constant 50 ohms.

The electrical conductivity routine in the datalogger returns the value

$$\frac{1}{Z_c}\frac{1-\rho}{1+\rho}$$

which must be multiplied by the probe constant, K_p, to get an electrical conductivity value.

The probe constant (K_p) is easily determined using PCTDR or can be determined through calibration. The probe rods are immersed in solutions of known electrical conductivity and values of $\frac{1}{Z_c}\frac{1-\rho}{1+\rho}$ collected by the datalogger. A linear regression of known electrical conductivity to the result from the datalogger will have a slope equal to the probe constant. When performing a calibration with independently measured electrical conductivity, take caution to account for the strong temperature dependence of electrical conductivity. This calibration is generally recommended if accurate absolute electrical conductivity values are required.

Laboratory calibrations were performed to determine a K_p value for the CS600, CS605 and CS610 probes with the following results.

TABLE 6-2. Probe Constant Values for Campbell Scientific Probes

Probe model	probe constant (K_p)
CS600	3.16
CS605 & CS610	1.74

Entering these constants as the multiplier when using Instruction 119 for electrical conductivity measurement will give units of Siemens/meter.

For example, when using a CS600 the value 3.16 can be entered into parameter 12 of Instruction 119 and the electrical conductivity value in Siemens per meter will be written to the input location specified in parameter 11.

6.3 CR1000 Datalogger Instruction "TDR100"

The TDR100 instruction is used to measure one or more time domain reflectivity (TDR) probes attached to a TDR100 device.

Syntax

TDR100 (Dest, SDMAddress, Option, Mux/ProbeSelect, WaveAvg, Vp, Points, CableLength, WindowLength, ProbeLength, ProbeOffset, Mult, Offset

Remarks

This instruction can be used to measure one TDR probe connected to the TDR100 directly or multiple TDR probes connected to one or more SDMX50 multiplexers.

Dest: The Dest parameter is a variable or variable array in which to store the results of the measurement. The variable must be dimensioned to accommodate all of the values returned by the instruction, which is determined by the Option parameter.

SDMAddress: The SDMAddress parameter defines the address of the TDR100 with which to communicate. Valid SDM addresses are 0 through 14. Address 15 is reserved for the SDMTrigger instruction. If the Reps parameter is greater than 1, the datalogger will increment the SDM address for each subsequent TDR100 that it communicates with.

NOTE CRBasic dataloggers use base 10 when addressing SDM devices. Edlog programmed dataloggers (e.g., CR10X, CR23X) used base 4 for addressing.

Option: The Option parameter determines the output of the instruction.

Code	Description
0	Measure La/L (ratio of apparent to physical probe rod length)
1	Collect Waveform values - Outputs reflection waveform values as an array of floating point numbers with a range of -1 to 1. The waveform values are prefaced by a header containing values of key parameters for this instruction (averaging, propagation velocity, points, cable length, window length, probe length, probe offset, multiplier, offset)
2	Collect Waveform plus First Derivative - Returns (2*n-5)+9 values where n is the number of waveform reflection values specified by the Points parameter.
3	Measure Electrical Conductivity - Outputs a value that when multiplied by the Multiplier parameter determines soil bulk electrical conductivity in S/m.

Mux/ProbeSelect: The Mux/Probe Select parameter is used to define the setup of any multiplexers and attached probes in the system. The addressing scheme used is ABCR, where A = level 1 multiplexer channel, B = level 2 multiplexer channel, C = level 3 multiplexer channel, and R = the number of consecutive probes to be read, starting with the channel specified by the ABC value (maximum of 8). 0 is entered for any level not used.

WaveAvg: The WaveAvg parameter is used to define the number of waveform reflections averaged by the TDR100 to give a single result. A waveform averaging value of 4 provides good signal-to-noise ratio under typical applications. Under high noise conditions averaging can be increased. The maximum averaging possible is 128.

Vp: The Vp parameter allows you to enter the propagation velocity of a cable when using the instruction to test for cable lengths or faults. Vp adjustment is not necessary for soil water content or electrical conductivity measurement and should be set to 1.0 for output Option 1, 2, or 3.

Points: The Points parameter is used to define the number of values in the displayed or collected waveform (20 to 2048). A entry of 251 is recommended for soil water measurements. The waveform consists of the number of Points equally spaced over the WindowLength.

CableLength: The CableLength parameter is used to specify the cable length, in meters, of the TDR probes. If a 0 is entered for the Option parameter, cable length is used by the analysis algorithm to begin searching for the TDR probe. If a 1 or 2 is entered for the Option parameter, cable length is the distance to the start of the collected waveform.

The value used for CableLength is best determined using PCTDR100 with the Vp = 1.0. Adjust the CableLength and WindowLength values in PCTDR100 until the probe reflection can be viewed. Subtract about 0.5 meters from the distance associated with the beginning of the probe reflection.

Note that the specified CableLength applies to all probes read by this instruction; therefore, all probes must have the same cable lengths.

WindowLength: The WindowLength parameter specifies the length, in meters, of the waveform to collect or analyze. The waveform begins at the CableLength and ends at the CableLength + WindowLength. This is an apparent length because the value set for Vp may not be the actual propagation velocity. For water content measurements, the WindowLength must be large enough to contain the entire probe reflection for probes with 20 to 30 cm rods. A Vp = 1 and Window length = 5 is recommended.

ProbeLength: The ProbeLength parameter specifies the length, in meters, of the probe rods that are exposed to the medium being measured. The value of this parameter only has an affect when Option 0, La/L, is used for the measurement.

ProbeOffset: The ProbeOffset is an apparent length value used to correct for the portion of the probe rods that may be encapsulated in epoxy and not surrounded by soil or other medium being measured. This value is supplied by Campbell Scientific for the probes we manufacture. The value of this

parameter only has an affect when Option 0, La/L, is used for the measurement.

Mult, Offset: The Mult and Offset parameters are each a constant, variable, array, or expression by which to scale the results of the measurement.

7. TDR Principles

The travel time for a pulsed electromagnetic signal along a waveguide is dependent on the velocity of the signal and the length of the waveguide. The velocity is dependent on the dielectric constant of the material surrounding the waveguide. This relationship can be expressed by

$$\Delta t = \frac{2L\sqrt{K_a}}{c} \qquad [1]$$

where K_a is the apparent dielectric constant, c is the velocity of electromagnetic signals in free space, Δt is the travel time, and L is the waveguide length. The dielectric constant of water relative to other soil constituents is high. Consequently, changes in volumetric water content can be directly related to the change in the dielectric constant of bulk soil material. Equation [1] can be simplified to express the apparent dielectric constant as the ratio of the apparent probe length ($L_a = c\Delta t/2$) to the real probe length.

$$\sqrt{K_a} = \frac{L_a}{L} \qquad [2]$$

The relationship between dielectric constant and volumetric water content has been described by, among others, Topp et al. (1980) and Ledieu et al. (1986) in an empirical fashion using both polynomial and linear forms. These expressions are presented here since it has been shown in numerous research efforts that these equations are appropriate for nearly all applications. With θ_v the volumetric water content, the equation presented by Topp et al. (1980) is

$$\theta_v = -5.3*10^{-2} + 2.92*10^{-2} K_a - 5.5*10^{-4} K_a^2 + 4.3*10^{-6} K_a^3 \qquad [3]$$

and that presented by Ledieu et al. (1986) is

$$\theta_v = 0.1138\sqrt{K_a} - 0.1758 \qquad [4]$$

The TDR100 generates a very fast rise time pulse that is sent to the connecting cable and probe. Reflections over a specified length of transmission line are sampled and digitized. Discontinuities in cable impedance will cause changes in the amplitude of the reflected signal. The travel time of the reflected signal is used with a velocity value to give distance information. A probe consisting of metal rods can be used as an extension of a coaxial cable. When the probe is inserted in the soil, the travel time of the applied pulse along the probe length will depend on the soil water content. In general, as the water content increases, the travel time of the applied pulse increases. The reflected waveform of the probe can be used to identify the impedance transitions

caused by the probe beginning and end. This information is then analyzed to determine soil water content.

While the velocity of the applied pulse along a waveguide is dependent on the dielectric constant of the material surrounding the waveguide, the amplitude of the reflected voltage is dependent on electrical conduction of the applied signal between probe rods. The presence of free ions in the soil solution will result in attenuation of the applied signal. Theory presented by Giese and Tiemann (1975) has been applied to the measurement of soil bulk electrical conductivity. A commonly used expression is

$$\sigma = \frac{K_p}{Z_c}\frac{1-\rho}{1+\rho} \qquad [5]$$

where σ is the bulk electrical conductivity, K_p is a probe constant, Z_c is the cable impedance (50 ohm), and ρ is the reflection coefficient. The reflection coefficient is the ratio of the reflected voltage to the applied voltage and ranges between plus and minus one.

The components of the Campbell Scientific TDR system are designed to apply time domain reflectometry for the determination of soil volumetric water content and bulk electrical conductivity as both hardware for the collection of data and software for communications and analysis of the data.

8. Cable Length and Soil Electrical Conductivity Effect on Water Content Determination

8.1 Cable Length Effect on Water Content Measurement

The determination of water content using the TDR system relies on the evaluation of a pulse reflection from the TDR probe. The pulse generated by the TDR100 and its reflections are subject to distortion during travel between the TDR100 and the TDR probe. The cable connecting the probe to the reflectometer has a characteristic impedance resulting in both resistive and reactive losses. Distortion of the waveform caused by cable impedance can introduce error into the water content determination.

Figure 8-1 presents waveforms collected from a 3-rod probe (CS610) for various cable lengths. As cable length increases, the rise time and the amplitude of the reflection are affected. The slopes and extrema used by the datalogger algorithm to analyze the waveform are shifted by the cable losses resulting in error. For the data shown in Figure 8-1, the water content measurement using the 66 meter cable was in error by about 1.5% volumetric water content when electrical conductivity is low. However, in saline soils the error can be several percent. See Bilskie (1997) for complete results of the study.

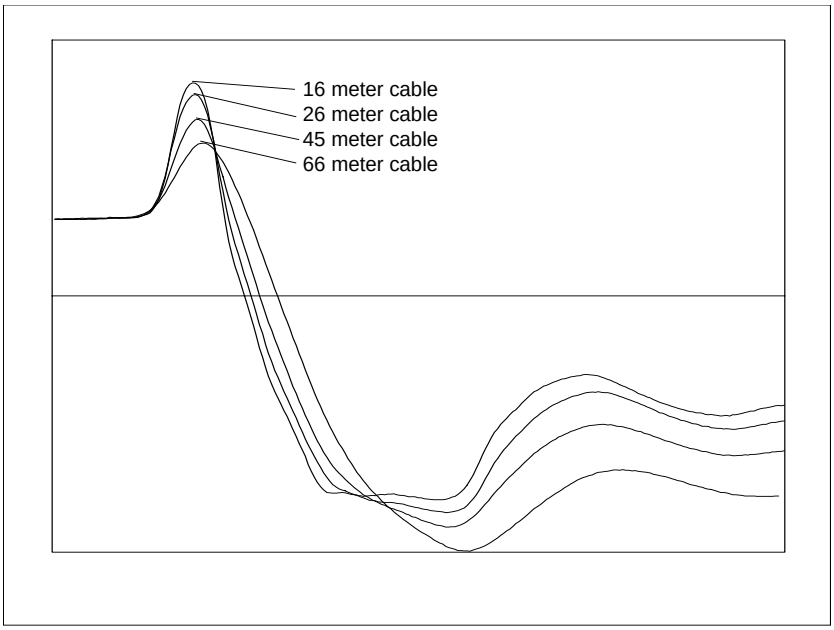


FIGURE 8-1. Waveforms collected in a sandy loam using CS610 probe with RG8 connecting cable. Volumetric water content is 24% and bulk electrical conductivity is 0.3 dS m^{-1}.

In general, water content is overestimated with increasing cable length. A calibration of volumetric water content with apparent dielectric constant for a given cable length can improve accuracy. Measurement precision at longer cable lengths will be maintained as long as soil electrical conductivity does not prevent a reflection from the end of the probe rods. This is discussed later in this section.

Minimizing cable lengths should always be considered in the design of a measurement system using TDR. If long cable lengths are necessary, the adverse effects can be minimized by using low attenuation cable such as RG8. Careful probe design ensures correct probe impedance giving robust reflections. All TDR probes offered by Campbell Scientific are designed to optimize accuracy when longer cable lengths are used.

8.2 Soil Electrical Conductivity Effect on Water Content Measurement

The signal at the probe will be attenuated when ionic conduction occurs in the soil solution. This inherent attenuation is used in TDR measurements to determine soil electrical conductivity as described by equation [5]. The presence of ions in the soil solution provides a path for electrical conduction between TDR probe rods. The attenuation of the signal can affect the accuracy and resolution of water content measurements. Figure 8-2 presents a series of waveforms when a solution with an electrical conductivity of 1.0 dS m^{-1} is added to a soil which has essentially no salt present. Figure 8-3 shows data for solution with high electrical conductivity.

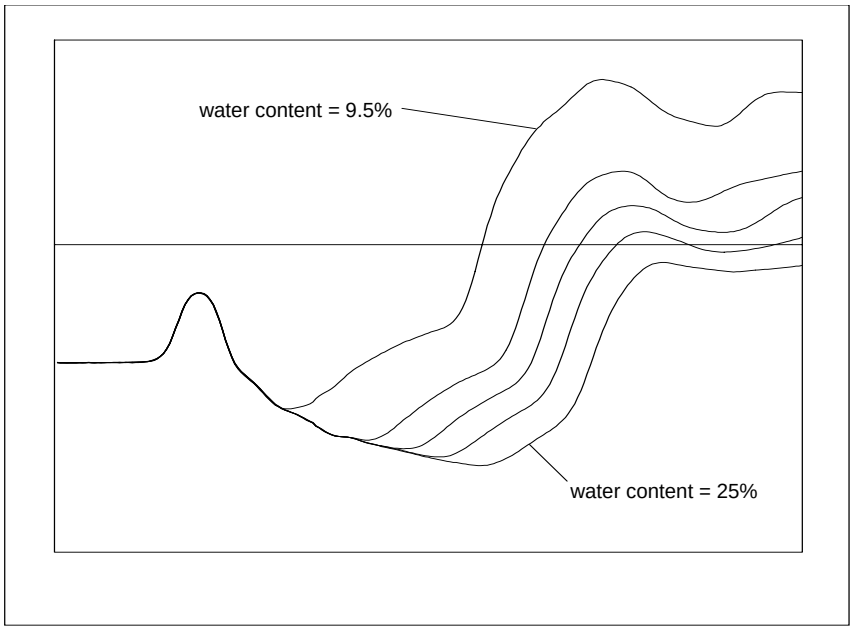


FIGURE 8-2. Waveforms collected in a sandy loam using CS610 probe with RG8 connecting cable. Volumetric water content values are 10, 16, 18, 21 and 25%. Solution electrical conductivity is 1.0 dS m^{-1}.

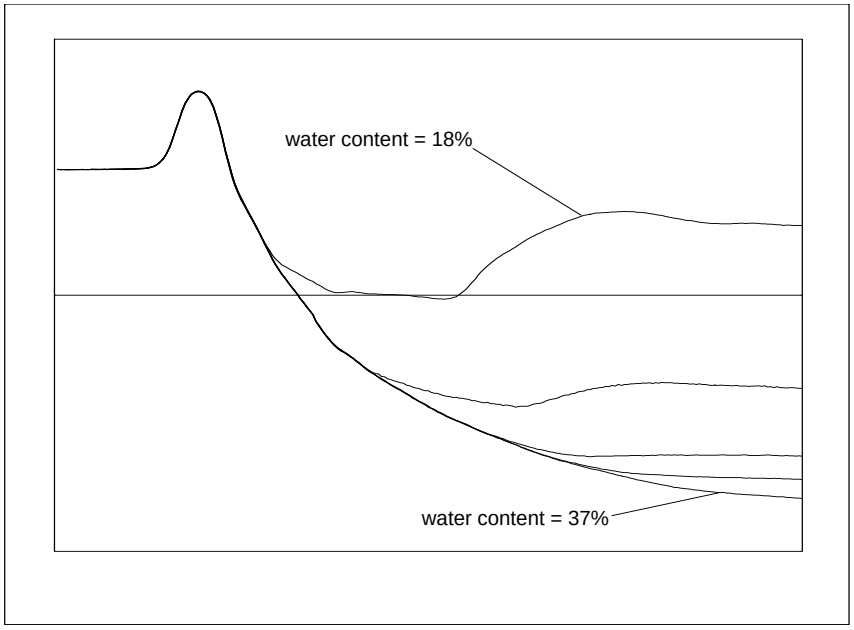


FIGURE 8-3. Waveforms collected in a sandy loam using CS610 probe with RG8 connecting cable. Volumetric water content values are 10, 18, 26, 30 and 37%. Solution electrical conductivity is 10.2 dS m^{-1}.

The combined effect of long cable runs and high soil electrical conductivity must be considered when TDR measurements are taken.

9. Programming Examples

9.1 CR10X/CR23X Program Examples

Example 1, Measure and Record; Analog Measurements and Volumetric Water Content

A CS605 or CS610 probe is connected directly to the TDR100. A cable length of 6.25 meters was determined using PCTDR. The L_a/L value is converted to volumetric water content using the Ledieu , etal linear calibration function. The program is executed once a minute. The array id, time, analog measurements, and volumetric water content are output to Final Storage every five minutes.

```
;{CR10X}
;
;Program Name = T100EX#1
;

*Table 1 Program
  01: 60            Execution Interval (seconds)

;Measure the datalogger power supply voltage:

1: Batt Voltage (P10)
  1:  1             Loc [ Bat_Volt  ]

;Measure the internal temperature of the datalogger:

2: Internal Temperature (P17)
  1:  2             Loc [ DL_Temp   ]

;Set port 5 high to switch ON "Switched 12V" power from the datalogger to power the TDR100.

3: Do (P86)
  1:  45            Set Port 5 High

;Measure the CS610 probe connected directly to the TDR100 and convert to water content:

4: TDR100 Measurement (P119)
  1:  0             SDM Address
  2:  0             La/L
  3:  0000          MMMP Mux & Probe Selection
  4:  4             Waveform Averaging
  5:  1             Vp
  6:  250           Points
  7:  5.75          Cable Length (meters)
  8:  5             Window Length (meters)
  9:  .3            Probe Length (meters)
  10: 0.085         Probe Offset (meters)
  11: 3             Loc [ WC_1      ]
  12: .1138         Mult                    ; Multiplier for Liedu Calibration
  13: -0.1758       Offset                  ; Offset for Liedu Calibration
```

```
;Turn off the switched 12V to power off the TDR100:

5:  Do (P86)
   1:   55              Set Port 5 Low

;Set the Output Flag to output data every 5 minutes:

6:  If time is (P92)
   1:   0               Minutes (Seconds --) into a
   2:   5               Interval (same units as above)
   3:   10              Set Output Flag High (Flag 0)

;Output a time stamp; year, day, and hour/minute:

7:  Real Time (P77)
   1:   1220            Year,Day,Hour/Minute (midnight = 2400)

;Output the minimum Battery Voltage:

8:  Minimum (P74)
   1:   1               Reps
   2:   0               Value Only
   3:   1               Loc [ Bat_Volt  ]

;Output the average Datalogger temperature and water content

9:  Average (P71)
   1:   2               Reps
   2:   2               Loc [ DL_Temp   ]

*Table 2 Program
   02:  0.0000          Execution Interval (seconds)

*Table 3 Subroutines

End Program
```

Example 2, Measure and Record; Analog Measurements, Volumetric Water Content, Electrical Conductivity, and Capture a Waveform

A CS605 or CS610 probe is connected to Channel #3 of a Level #1 SDMX50 Multiplexer. A cable length of 9.5 meters was determined using PCTDR. The La/L value is converted to volumetric water content using the Topp's calibration (Section 7). The program is executed every one minute while Flag 1 is High. The user can set Flag 1 high or low to control when data are stored. The array id, time, analog measurements, volumetric water content are output to Final Storage once a minute.

```
;{CR10X}
;
;Program Name = T100EX#2
;

*Table 1 Program
  01: 60            Execution Interval (seconds)

;The following P91 instruction allows the user to control when measurements are made and stored.
;When Flag 1 is low program execution jumps to the end of the table and no data acquisition will
occur.
;Flag 1 is a user flag and must be set by the user. This is done from the connect screen in PC208W
or LoggerNet;or using the keyboard display with the *6 Mode D command. The default status for
Flags 1 is low.
;This instruction can be removed if the user does not want to manually trigger data acquisition.

1: If Flag/Port (P91)
  1:  21            Do if Flag 1 is Low
  2:  0             Go to end of Program Table

;Measure the datalogger power supply voltage:

2: Batt Voltage (P10)
  1:  1             Loc [ Bat_Volt  ]

;Measure the internal temperature of the datalogger:

3: Internal Temperature (P17)
  1:  2             Loc [ DL_Temp   ]

;Set port 5 high to switch ON "Switched 12V" power from the datalogger to power the TDR100.

4: Do (P86)
  1:  45            Set Port 5 High
```

```
;Measure the CS610 probe connected to Channel 3 of the level 1 SDMX50 and return La/L.

5:  TDR100 Measurement (P119)
   1:   0          SDM Address
   2:   0          La/L
   3:   3001       MMMP Mux & Probe Selection
   4:   4          Waveform Averaging
   5:   1          Vp
   6:   250        Points
   7:   9.5        Cable Length (meters)
   8:   5          Window Length (meters)
   9:   .3         Probe Length (meters)
   10:  .085       Probe Offset (meters)
   11:  3          Loc [ LaL_CH3   ]
   12:  1.0        Mult
   13:  0.0        Offset

;Square La/L to convert to dielectric constant:

6:  Z=X*Y (P36)
   1:   3          X Loc [ LaL_CH3   ]
   2:   3          Y Loc [ LaL_CH3   ]
   3:   4          Z Loc [ WC_CH3    ]

;Multiply the dielectric constant by 0.1 to prepare for the 3rd order polynomial
;with the appropriately scaled coefficients for Topp's calibration:

7:  Z=X*F (P37)
   1:   4          X Loc [ WC_CH3    ]
   2:   0.1        F
   3:   4          Z Loc [ WC_CH3    ]

;Apply Topp's 3rd order polynomial:

8:  Polynomial (P55)
   1:   1          Reps
   2:   4          X Loc [ WC_CH3    ]
   3:   4          F(X) Loc [ WC_CH3    ]
   4:   -0.053     C0
   5:   .292       C1
   6:   -0.055     C2
   7:   0.0043     C3
   8:   0.0        C4
   9:   0.0        C5
```

```
;Measure Electrical Conductivity on the same CS610 TDR probe connected to Channel 3.

9:  TDR100 Measurement (P119)
   1:   0          SDM Address
   2:   3          Electrical Conductivity
   3:   3001       MMMP Mux & Probe Selection
   4:   4          Waveform Averaging
   5:   1          Vp
   6:   250        Points
   7:   9.5        Cable Length (meters)
   8:   5          Window Length (meters)
   9:   .3         Probe Length (meters)
   10:  .085       Probe Offset (meters)
   11:  5          Loc [ EC_CH3    ]
   12:  7.4        Mult
   13:  0.0        Offset

;Get the raw waveform for the CS610 probe on Channel 3.
;When creating this program in Edlog, the user must reserve 259 input locations
;for data storage. How? In Edlog click on
;"Edit", select "Input Labels". In the Input Location Editor click on "Edit", select
;"Insert Block", and identify 259 input storage location for the captured waveform.
;Note: 9 parameter elements + 250 waveform data points = 259 input location/waveform.

10:  TDR100 Measurement (P119)
   1:   0          SDM Address
   2:   1          Waveform (256 locs)
   3:   3001       MMMP Mux & Probe Selection
   4:   4          Waveform Averaging
   5:   1          Vp
   6:   250        Points
   7:   9.5        Cable Length (meters)
   8:   5          Window Length (meters)
   9:   .3         Probe Length (meters)
   10:  .085       Probe Offset (meters)
   11:  11         Loc [ WF_1      ]
   12:  1.0        Mult
   13:  0.0        Offset

;Turn off the switched 12V to power off the TDR100:

11:  Do (P86)
   1:   55         Set Port 5 Low

;Set the Output Flag to output data each time measurements are made:

12:  Do (P86)
   1:   10         Set Output Flag High (Flag 0)

;Output a time stamp; year, day, and hour/minute:

13:  Real Time (P77)
   1:   1220       Year,Day,Hour/Minute (midnight = 2400)
```

```
;Output the Battery_Voltage, DataLogger Temperature, WaterContent,
;and Electrical Conductivity.

14:  Sample (P70)
   1:   4              Reps
   2:   1              Loc [ Bat_Volt  ]

;Output the WaveForm data point 1 to WaveForm data point 259:

15:  Sample (P70)
   1:   259            Reps
   2:   11             Loc [ WF_1      ]


*Table 2 Program
   02:  0.0000         Execution Interval (seconds)

*Table 3 Subroutines

End Program
```

Example 3, Measure and Record; Volumetric Water Content and Analog Measurements

Eight CS605 or CS610 probes are connected to Channel #1 through #8 of a Level #1 SDMX50 multiplexer. A cable length value of 10 meters was determined using PCTDR. The La/L value is converted to volumetric water content using the Topp calibration. The program is executed every two minutes. The array id, time, volumetric water content and analog measurements are output to Final Storage every two minutes.

```
;{CR10X}
;
;Program Name: T100EX#3
;
*Table 1 Program
  01: 120           Execution Interval (seconds)

;Set port 5 high to switch ON "Switched 12V" power from the datalogger to power the TDR100.

1: Do (P86)
  1:  45           Set Port 5 High

;Measure the 8 CS610 probes connected to the level 1 SDMX50, return La/L:
;When creating the program with edlog, the user must manually allocate the 8 input
;locations (i.e.: "LaL_1" through LaL_8"). For Edlog's help on how to do this,
;right mouse click the La/L parameter, select help, then click on
;"manually inserting input locations in Edlog".

2: TDR100 Measurement (P119)
  1:  00           SDM Address
  2:  0            La/L
  3:  1008         MMMP Mux & Probe Selection
  4:  4            Waveform Averaging
  5:  1            Vp
  6:  250          Points
  7:  9.5          Cable Length (meters)
  8:  5            Window Length (meters)
  9:  .3           Probe Length (meters)
  10: .085         Probe Offset (meters)
  11: 1            Loc [ LaL_1     ]
  12: 1            Mult
  13: 0            Offset

;Turn off the switched 12V to power off the TDR100:

3: Do (P86)
  1:  55           Set Port 5 Low

;The following loop applies Topp's calibration to the 8 La/L values.
;One La/L value is converted with each pass through the loop. The indexed
;input locations (those with "--" to the right) are incremented each
;pass through the loop.  (Index an input location in Edlog by pressing "F4"
;while the input location is highlighted).
```

```
4:  Beginning of Loop (P87)
   1:   0              Delay
   2:   8              Loop Count

;Square La/L to convert to dielectric constant:
;Note: The user must manually allocate 8 input locations "WC_1" through WC_8".

5:  Z=X*Y (P36)
   1:   1              -- X Loc [ LaL_1     ]
   2:   1              -- Y Loc [ LaL_1     ]
   3:   11             -- Z Loc [ WC_1      ]

;Multiply the dielectric constant by 0.1 to prepare for the 3rd order polynomial
;with the appropriately scaled coefficients for Topp's calibration:

6:  Z=X*F (P37)
   1:   11             -- X Loc [ WC_1      ]
   2:   0.1            F
   3:   11             -- Z Loc [ WC_1      ]

;Apply Topp's 3rd order polynomial:

7:  Polynomial (P55)
   1:   1              Reps
   2:   11             -- X Loc [ WC_1      ]
   3:   11             -- F(X) Loc [ WC_1      ]
   4:   -0.053         C0
   5:   .292           C1
   6:   -0.055         C2
   7:   0.0043         C3
   8:   0.0            C4
   9:   0.0            C5

8:  End (P95) ; End of the Loop.

;Measure the datalogger power supply voltage:

9:  Batt Voltage (P10)
   1:   19             Loc [ Bat_Volt  ]

;Set the Output Flag to output data each time measurements are made:

10:  Do (P86)
   1:   10             Set Output Flag High (Flag 0)

;Output a time stamp; year, day, and hour/minute:

11:  Real Time (P77)
   1:   1220           Year,Day,Hour/Minute (midnight = 2400)
```

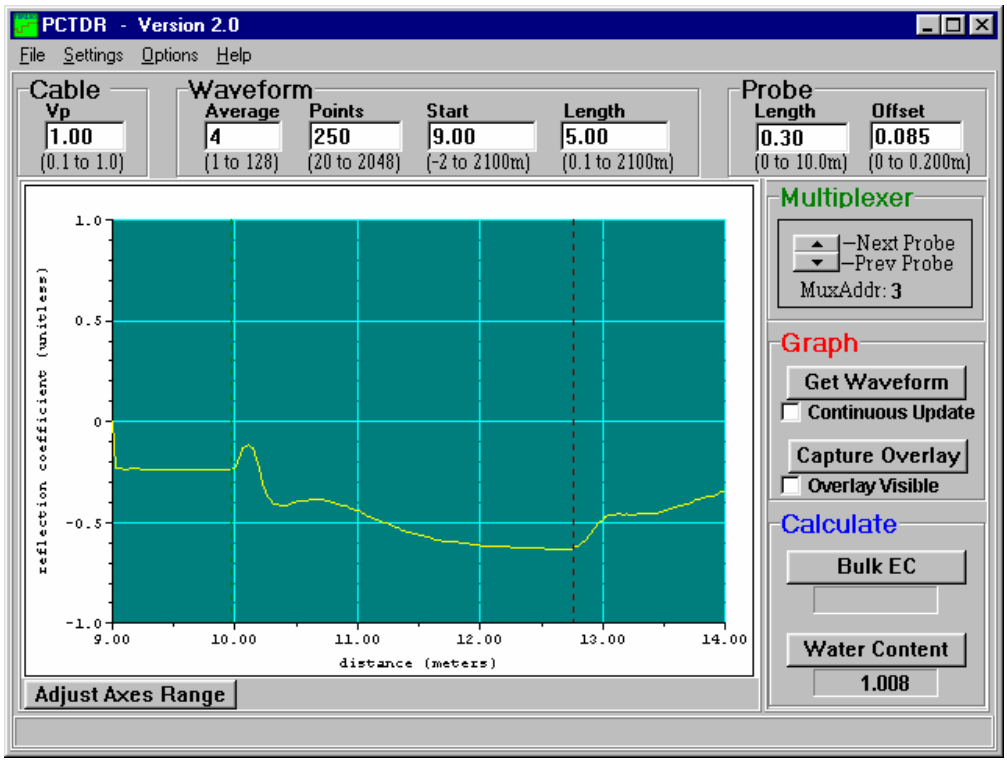
```
;Output the 8 water content measurements and battery voltage:

12:  Sample (P70)
   1:   9              Reps
   2:   11             Loc [ WC_1      ]

*Table 2 Program
   02:  0.0000         Execution Interval (seconds)

*Table 3 Subroutines

End Program
```



Example 4, Measure and Record; Analog Measurements and Volumetric Water Content

In this example analog measurements are made every 5 minutes and TDR100 measurements are made every 60 minutes. Twenty-nine CS605 or CS610 probes are connected to 4 SDMX50 multiplexers (Figure 9-1). The cable length values were determined using PCTDR. The La/L value is converted to volumetric water content using the linear calibration function of Ledieu, etal. (1986). The program is executed every 5 minutes. The array id, time, average of the analog measurements and the volumetric water content measurement are output to Final Storage once an hour.

```
;{CR10X}

;Program = T100EX#4

*Table 1 Program
  01: 300           Execution Interval (seconds)

;Every 5 minutes (300 second execution interval)
;Measure the datalogger power supply voltage:

1: Batt Voltage (P10)
  1:  1             Loc [ Bat_Volt  ]

;Measure the internal temperature of the datalogger:

2: Internal Temperature (P17)
  1:  2             Loc [ DL_Temp   ]

;Once an hour on the hour (0 minutes into a 60 minute interval)
;Measure the TDR probes:

3: If time is (P92)
  1:  0             Minutes (Seconds --) into a
  2:  60            Interval (same units as above)
  3:  30            Then Do

;Set port 5 high to switch ON "Switched 12V" power from the datalogger to power the TDR100.

4: Do (P86)
  1:  45            Set Port 5 High

;Measure the 6 CS610 probes connected to the Level 1 SDMX50
;(Channels 3 to 8) and convert to water content:
```

```
5:  TDR100 Measurement (P119)
   1:   00          SDM Address
   2:   0           La/L
   3:   3006        MMMP Mux & Probe Selection
   4:   4           Waveform Averaging
   5:   1           Vp
   6:   250         Points
   7:   5.75        Cable Length (meters)
   8:   5           Window Length (meters)
   9:   .3          Probe Length (meters)
   10:  .085        Probe Offset (meters)
   11:  11          Loc [ WC_3001   ]
   12:  1138        Mult
   13:  -0.1758     Offset

;Switch the level 1 SDMX50 to Channel 1 and measure the 8 probes on the Level 2
;multiplexer that is connected to channel 1 of the level 1 mux (apparent cable length to
;probe 9.5 meters):

6:  TDR100 Measurement (P119)
   1:   00          SDM Address
   2:   0           La/L
   3:   1108        MMMP Mux & Probe Selection
   4:   4           Waveform Averaging
   5:   1           Vp
   6:   250         Points
   7:   9.5         Cable Length (meters)
   8:   5           Window Length (meters)
   9:   .3          Probe Length (meters)
   10:  .085        Probe Offset (meters)
   11:  17          Loc [ WC_1101   ]
   12:  1138        Mult
   13:  -0.1758     Offset

;Switch the level 1 SDMX50 to Channel 2 and measure the 7 probes
;(channels 1 through 7) on the Level 2 multiplexer that is connected to channel 2
;of the level 1 mux (apparent cable length to probe 10 meters):

7:  TDR100 Measurement (P119)
   1:   00          SDM Address
   2:   0           La/L
   3:   2107        MMMP Mux & Probe Selection
   4:   4           Waveform Averaging
   5:   1           Vp
   6:   250         Points
   7:   9.5         Cable Length (meters)
   8:   5           Window Length (meters)
   9:   .3          Probe Length (meters)
   10:  .085        Probe Offset (meters)
   11:  25          Loc [ WC_2101   ]
   12:  1138        Mult
   13:  -0.1758     Offset
```

```
;Switch the level 1 SDMX50 to Channel 2, the level 2 SDMX50s to Channel 8 and
;measure the 8 probes (channels 1 through 8) on the Level 3 SDMX50
;(aparent cable length to probe 10 meters):

8:  TDR100 Measurement (P119)
   1:   00          SDM Address
   2:   0           La/L
   3:   2818        MMMP Mux & Probe Selection
   4:   4           Waveform Averaging
   5:   1           Vp
   6:   250         Points
   7:   25.0        Cable Length (meters)
   8:   5           Window Length (meters)
   9:   .3          Probe Length (meters)
   10:  .085        Probe Offset (meters)
   11:  32          Loc [ WC_2811   ]
   12:  1138        Mult
   13:  -0.1758     Offset

;Turn off the switched 12V to power off the TDR100:

9:  Do (P86)
   1:   55          Set Port 5 Low

;Now, after making the measurents, set the output flag.
;Remember this is only done once an hour

10:  Do (P86)
   1:   10          Set Output Flag High (Flag 0)

;Instruction 80 is used to set the output Array ID to 60:

11:  Set Active Storage Area (P80)
   1:   1           Final Storage Area 1
   2:   60          Array ID

12:  End (P95) ; End of Instructions to execute once an hour

;The following instructions only send data to Final Storage once
;an hour when the Output flag is set.

;Output a time stamp; year, day, and hour/minute:

13:  Real Time (P77)
   1:   1220        Year,Day,Hour/Minute (midnight = 2400)

;Output the averages of the 5 minute measurements of Batery Voltage
; and Datalogger temperature:

14:  Average (P71)
   1:   2           Reps
   2:   1           Loc [ Bat_Volt  ]
```

```
;Output the 29 TDR water content measurements:

15:  Sample (P70)
   1:   29            Reps
   2:   11            Loc [ WC_3001   ]


*Table 2 Program
   02:  0.0000        Execution Interval (seconds)

*Table 3 Subroutines

End Program
```

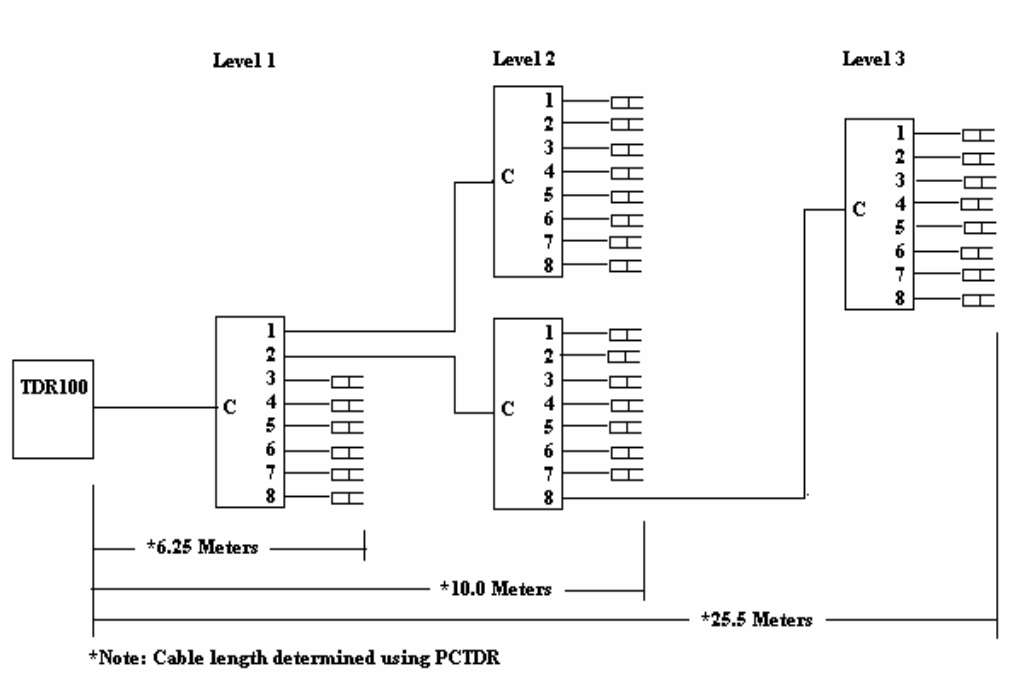


FIGURE 9-1. Twenty-nine CS605 or CS610 probes connected to 4ea SDMX50 multiplexers.

Example 5, Trouble Shooting Program for SDMX50 Multiplexer, Datalogger Control Ports, and Analog Measurements

The following program can be used to test the operation of the SDMX50 Multiplexer and the datalogger control ports.

```
;{CR10X}

;Program Name: Example 5

*Table 1 Program
  01: 5             Execution Interval (seconds)

;The Following Instruction 20 configures all 8 Control Ports as Outputs.
;This allows the user to manually set the ports high (+5V) or low (0V) in order
;to check the port operation with a volt meter. Ports and flags can be set with
;the Keyboard Display (*6 Mode, Datalogger Manual Section 1.3) or from the Connect
;Screen of PC208W or LoggerNet.

1: Set Port(s) (P20)
  1: 7777         C8..C5 = output/output/output/output
  2: 7777         C4..C1 = output/output/output/output

;To test wiring and multiplexer operation, the user can set Flag 1 and
;Instruction 109 will switch the SDMX50 multiplexer(s) to channel 8.
;(Starting at channel 1 each time P109 is executed.)
;If Flag 1 is LOW  Instruction 109 will NOT be executed. The default
;status for User Flags 1-8 is low.
;NOTE: While Flag 1 is high Intruction 109 will take control of the
;SDM ports 1-3. It may not be possible to follow the ports
;going High and low with a voltmeter while this is happening.

2: If Flag/Port (P91)
  1: 11           Do if Flag 1 is High
  2: 30           Then Do

3: SDMX50 Channel Select (P109)
  1: 01           SDM Address          ; Enter correct address for connected multiplexer
  2: 8            SDM Channel

4: End (P95)                           ;End, If Flag 1

*Table 2 Program
  02: 0.0000      Execution Interval (seconds)

*Table 3 Subroutines

End Program
```

9.2 CR1000 Program Example

Example 1, Measure and Record; Analog Measurements, Volumetric Water Content, and Capture TDR Probe Waveforms

Equipment Wiring		
CR1000	**TDR100**	**SDMX50**
SW12	+12 V	12 V
G	G	G
C1	C1	C1
C2	C2	C2
C3	C3	C3

Sensor Wiring		
TDR100	**SDMX50**	**TDR Probe***
Coax	Common	
	Channel_1	Probe 1
	Channel_2	Probe 2
	Channel_3	Probe 3
	Channel_4	Probe 4
	Channel_5	Probe 5
	Channel_6	Probe 6
	Channel_7	Probe 7
	Channel_8	Probe 8
*Note: TDR probe cable length must be determined using PCTDR!		

```
'CR1000 Series Datalogger

'program: c:\mydoc\cr1000\cr1000-testing\TDR&SDM&F1&Wave_CR1K.CR1
'date: 10-27-04
'Measure and Record Analog Measurements, Volumetric Water Content, & Store Waveforms
'
'Declare Public & Dim Variables ----------------------------------
Public batt_volt
Public Panel_temp
Public LaL(8)
Public LaL2(8)
Public LedieuVWC(8)
Public ToppVWC(8)
```

```
Public Flag(2)
public WavePT(260)
public MuxChan
Dim I

'Declare Constants -------------------------------------------------
'Topp Equation Dielectric Constants
const a0= -0.053
const a1= 0.0292
const a2= -0.00055
const a3= 0.0000043
I
const high = true
const low = false

'Define Data Tables ------------------------------------------------
DataTable (Dat15min,1,-1)                    '15-minute Data Table (i.e. Analog Measurements)
    DataInterval (0,15,Min,10)
    Minimum (1,batt_volt,IEEE4,0,False)
    Average (1,Panel_temp,IEEE4,0)
EndTable

DataTable (Data_TDR,1,-1)                    '2-Hour Data Table (i.e. TDR100 VWC Measurements)
    DataInterval (0,120,Min,10)
    Minimum (1,batt_volt,IEEE4,0,False)
    Average (1,Panel_temp,IEEE4,0)
    Sample (8,LaL(),IEEE4)
    sample (8,LedieuVWC(),FP2)
    sample (8,ToppVWC(),FP2)
EndTable
'
DataTable (TDR_Wave,1,240)                   'Data Table (i.e. Capture TDR Probe Waveforms)
    sample (1,MuxChan,IEEE4)
    sample (260,WavePT(),FP2)
EndTable
'Note: The DataTable "TDR_Wave" data storage area is NOT and should NOT be auto allocated
'in this program example!!! Therefore, "TDR_Wave" memory storage size should be allocated
'by the programmer. How to calculate memory storage size?
'Example: In this program when F2 goes high there are 8ea calls to "TDR_Wave", repeated
'let's say 30 times, will allocate memory for 240 waveforms. "DataTable (TDR_Wave,1,240)"
'
'Main Program ------------------------------------------------------
BeginProg
    SDMSpeed (50)                            'Fix TDR100 to CR1K communication timing
    '
    Scan (5,Sec,0,0)                         'scan instructions every 5 sec
        Battery (Batt_volt)
        PanelTemp (Panel_temp,250)
        CallTable Dat15min
        '
        'Set flag 1 High every 120 minutes (Note: User can manually set flag 1 high/low)
        If TimeIntoInterval(0,2,Hr) Then Flag(1)=High
        'Set flag 2 High once per day (Note: User can manually set flag 2 high/low)
```

```
If TimeIntoInterval(0,24,Hr) then flag(2)=high  '
If Flag(1)=High Then                        '**************************************
    SW12 (1)                                'Turn on 12V Power to TDR100 & SDMX50
    'Note: Wire TDR100 & SDMX50 12V power leads to CR1000 SW12 Terminal
    Delay (1,2,Sec)                         'pause 2 sec to allow power supply voltage to settle
    '
    'Measure La/L on SDMX50 channel #1 thru channel#8 & convert to VWC using Topp Eq.
    TDR100 (LaL(1),0,0,1001,4,1.0,251,9.5,5.0,0.3,0.085,1,0)
    TDR100 (LaL(2),0,0,2001,4,1.0,251,9.0,5.0,0.3,0.085,1,0)
    TDR100 (LaL(3),0,0,3001,4,1.0,251,8.5,5.0,0.3,0.085,1,0)
    TDR100 (LaL(4),0,0,4001,4,1.0,251,9.5,5.0,0.3,0.085,1,0)
    TDR100 (LaL(5),0,0,5001,4,1.0,251,7.0,5.0,0.3,0.085,1,0)
    TDR100 (LaL(6),0,0,6001,4,1.0,251,10.5,5.0,0.3,0.085,1,0)
    TDR100 (LaL(7),0,0,7001,4,1.0,251,11.5,5.0,0.3,0.085,1,0)
    TDR100 (LaL(8),0,0,8001,4,1.0,251,9.5,5.0,0.3,0.085,1,0)
    For I=1 to 8
        LaL2(I) = LaL(I)^2                  'Apparent Dielectric Constant K = (La/L)^2
    Next I
    'Topp Conversion from Dielectric Constant to Volumetric Water Content (VWC)
    For I=1 to 8
        ToppVWC(I)=a0 + a1*LaL2(I) + a2*LaL2(I)^2 + a3*LaL2(I)^3
    Next I
    '
    'Measure La/L on SDMX50 channel #1 thru channel#8 & convert to VWC using Ledieu Eq.
    'Note: Reps (i.e. "1008") assume all cables are the same length!!!
    TDR100 (LedieuVWC(),0,0,1008,4,1.0,251,9.5,5.0,0.3,0.085,.1138,-0.1758)
    '
    CallTable Data_TDR
    Flag(1)=0                               'reset state of Flag 1
    SW12 (0 )                               'Switched 12V Low
endif                                       'EndIf for Flag 1 ************************

If Flag(2)=High Then                        '**************************************
    SW12 (1)                                'Turn on 12V Power to TDR100 & SDMX50
    Delay (0,2,Sec)                         'pause 2 sec to allow power supply voltage to settle out
    '
    MuxChan=1001                            'store the SDMX50 channel in variable "MuxChan"
    TDR100 (WavePT(),0,1,1001,4,1.0,251,9.5,5.0,0.3,0.085,1,0)
    CallTable TDR_Wave()
    '
    MuxChan=2001                            'store the SDMX50 channel in variable "MuxChan"
    TDR100 (WavePT(),0,1,2001,4,1.0,251,9.5,5.0,0.3,0.085,1,0)
    CallTable TDR_Wave()
    '
    MuxChan=3001
    TDR100 (WavePT(),0,1,3001,4,1.0,251,9.5,5.0,0.3,0.085,1,0)
    CallTable TDR_Wave()
    '
    MuxChan=4001
    TDR100 (WavePT(),0,1,4001,4,1.0,251,9.5,5.0,0.3,0.085,1,0)
    CallTable TDR_Wave()
    '
    MuxChan=5001
    TDR100 (WavePT(),0,1,5001,4,1.0,251,9.5,5.0,0.3,0.085,1,0)
    CallTable TDR_Wave()
    '
    MuxChan=6001
```

```
            TDR100 (WavePT(),0,1,6001,4,1.0,251,9.5,5.0,0.3,0.085,1,0)
            CallTable TDR_Wave()
            '
            MuxChan=7001
            TDR100 (WavePT(),0,1,7001,4,1.0,251,9.5,5.0,0.3,0.085,1,0)
            CallTable TDR_Wave()
            '
            MuxChan=8001
            TDR100 (WavePT(),0,1,8001,4,1.0,251,9.5,5.0,0.3,0.085,1,0)
            CallTable TDR_Wave()
            '
            Flag(2)=0                                   'reset state of Flag 2
            SW12 (0 )                                   'Switched 12V Low
        endif                                           'EndIf **********************************
        '
        PortsConfig (&B00000111,&B00000000)   'configure SDM ports C1,C2,C3 as inputs
        '
    NextScan
EndProg
```

10. References

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